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The *Kepler Mission*: Astrophysics and Eclipsing Binaries

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Abstract
The *Kepler Mission* is a photometric space mission that will continuously observe a single 100 square degree field of view (FOV) of the sky of more than 100,000 stars in the Cygnus-Lyra region for four or more years with a precision of 14 parts per million (ppm) for a 6.5 hour integration including shot noise for a twelfth magnitude star. The primary goal of the mission is to detect Earth-size planets in the habitable zone of solar-like stars. In the process, many eclipsing binaries (EB) will also be detected. Prior to launch, the stellar characteristics will have been determined for all the stars in the FOV with K<14.5. As part of the verification process, stars with transits (about 5%) will need to have follow-up radial velocity observations performed to determine the component masses and thereby separate grazing eclipses caused by stellar companions from transits caused by planets. The result will be a rich database on EBs. The community will have access to the archive for uses such as for EB modeling of the high-precision light curves. A guest observer program is also planned for objects in the field of view but not already on the target list.

Introduction
The *Kepler Mission* is the tenth principal investigator-lead mission selected in the NASA Discovery program series. The primary objective is to detect Earth-size and smaller planets in the habitable zone of solar-like stars. The mission concept is given in detail by Borucki, et al (2005). In summary, *Kepler* is a photometric space-based mission designed specifically for finding habitable planets, that is, those between about one-half to ten Earth masses and in the habitable zone (HZ) of solar-like stars, that is, near 1 AU. The HZ is taken to be the distance from a star where liquid water can exist on the surface of the planet (Kasting, Whitmire, and Reynolds, 1993). Although *Kepler* is optimized for the above case, its envelope for detection will clearly span many possibilities, especially the case for planets in shorter period orbits and for sizes significantly less than Earth. Figure 1 shows the detectable size dependence on 1) the planet's orbit, 2) the mission duration, 3) the stellar type and 4) total noise (1σ) defined as CDPP. The combined differential photometric precision (CDPP) includes shot noise, instrument measurement noise and an assumed stellar

variability of 10 ppm in the time domain of a transit - a few hours to about a half of a day. The figure is based on equation (1) (Koch, et al, 2004) for grazing transits that are only half as long as a central transit, detection of at least four transits, and a combined signal to noise ratio of 8σ for all the transits from a given planet detection. The figure should be applicable to any mission with continuous data and the appropriate CDPP.

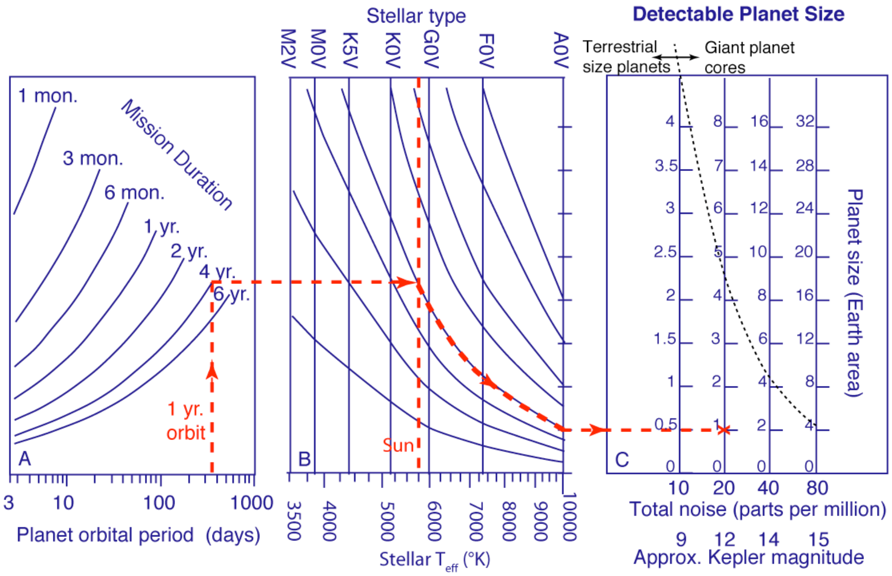

Figure 1 Detectable planet size. The dashed line illustrates, that for a one-year planetary orbit, a four-year mission, a solar like star, G2V (T_{eff}=5780°K), and a total noise of 20 ppm (including 10 ppm of stellar variability), that a one-Earth-size planet is detectable at 8σ. For other cases, select an orbital period in plot A and draw a vertical line up to the curve for the mission duration. Then draw a horizontal line to the desired stellar type or stellar effective temperature in plot B. The intersection of the horizontal line with the stellar type defines the "noise/size" curve to use or path to follow in between curves. Follow along the curve to the right edge of plot B. Draw a horizontal line to plot C to the appropriate total noise scale and read the value for the planet size. The dotted line in plot C is the approximate boundary between terrestrial-size planets and giant-planet cores.

Kepler will continuously and simultaneously observe over 100,000 main-sequence stars, using a one-meter Schmidt telescope with a FOV of greater than 100 square degrees and an array of 42 CCDs with 95 million pixels. The *Kepler* photometer (Figure 2) will be the ninth largest Schmidt ever built and the largest ever launched into space. The spacecraft will be launched into an Earth-trailing heliocentric orbit. This allows for continuous viewing of the selected FOV throughout the orbital year. In the process of performing the search for extra-solar terrestrial-size planets, the mission will produce a photometric database of unprecedented precision, duration and number of stars. In addition, *Kepler* has the capability to perform photometric observations of other astrophysical objects that are within its FOV as part of a guest observing program.

The Photometric Capabilities

Kepler will continuously observe the same FOV for four to six years, except for less than one day every three months when the spacecraft needs to be rotated 90° to keep the Sun on the solar arrays and the radiator used to cool the CCDs pointed to deep space. Data will have fifteen-minute time resolution, except that for 512 objects a one-minute time resolution is available. This will be used primarily to obtain finer time resolution of high signal to noise ratio transits (a Jupiter-size transit will have an SNR=800) and for measurement of p-mode oscillations in stars brighter than R=12. The combined noise from the instrument, stray light, background stars, etc. is expected to be 6.6 ppm for a 6.5-hour integration. The noise including both the observational noise and photon shot noise for R=12 is expected to be 16 ppm in 6.5 hours. Assuming a stellar variability in the time domain of a transit to be 10 ppm, yields a CDPP=20 ppm. A broad bandpass from 430 to 890 nm (50%) was chosen to minimize the shot noise. The bandpass was also chosen to avoid the variability in Ca II H& K in the blue and fringing in the CCDs in the red. The point spread function FWHM is about 12 arc sec (one pixel is 3.98 arc sec) and was chosen to minimize the effects of pointing jitter and sensitivity to spatial variations in the CCDs (Koch et al, 2000).

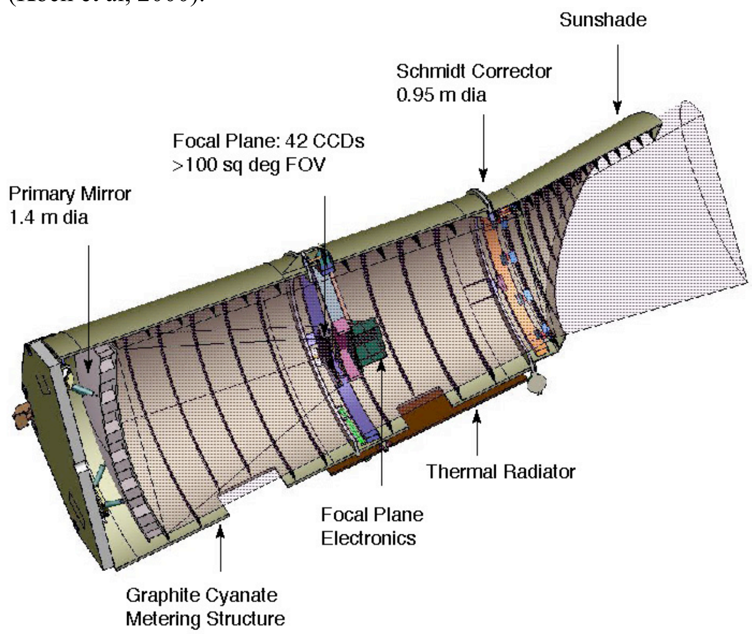

Figure 2 Cross sectional view of the *Kepler* photometer

Field Of View

Unlike almost all other astrophysics missions, *Kepler* will point to a single FOV for the entire mission. The objective was to select a single region with the richest field and to obtain the longest possible continuous exposure. The FOV choice was constrained to be above 55° ecliptic latitude, so as not to be blocked by the Sun at anytime during its orbit. The net result was a field slightly off the galactic plane centered at RA $19^h22^m40^s$ and declination 44°30'. The positions of the individual CCDs on the sky are shown in Figure 3. The layout is four-fold symmetric, which permits the 90° rotation while maintaining the same FOV on active silicon. Except for the central module, the orientation of CCD rows and columns is the same for all four rotations.

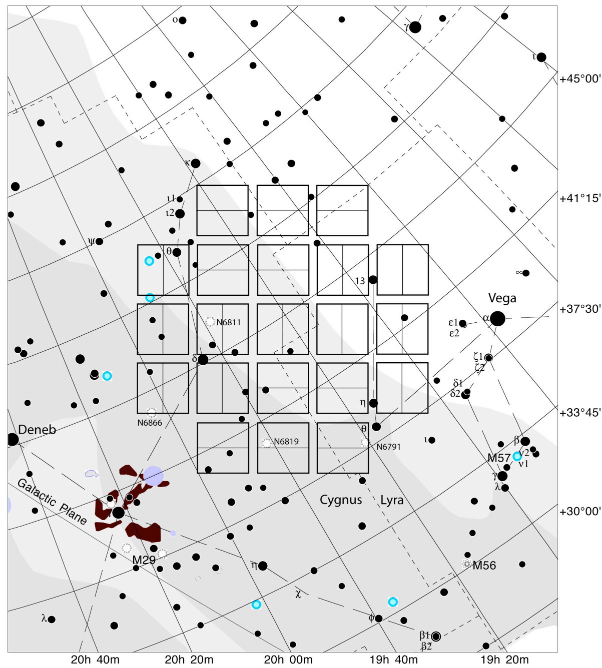

Figure 3 Layout of the CCD modules within the FOV in the Cygnus-Lyra region.

Stellar Classification Program

Given the scientific goal of finding planets around solar-like stars, we want to preferentially select late dwarfs of spectral types F, G, K and M. Since there does not exist a catalog that has luminosity classes to the necessary magnitude limits, the *Kepler* project is producing a catalog for the field of view. The stellar classification program (SCP) is making new multi-band photometric observations using the SDSS filter bandpasses plus a few additional filters to aid in estimating log(g). These data are analyzed using model fitting to derive, effective temperature, log(g) and radius, metallicity, extinction and reddening. The catalog has an observing limit to 18th magnitude and a classification limit of K=14.5. The catalog will be federated with other catalogs, such as 2MASS and USNO-B, to provide a cross reference. The catalog will be available to the community prior to launch.

Data Processing and Analysis

The data are processed in several phases on-board the spacecraft and on the ground. On-board, the CCDs are read out about every five seconds. All 95 megapixels are accumulated on board in memory for fifteen minutes. At the end of each fifteen-minute integration, only the pixels of interest associated with each preselected star are stored and later transmitted to the ground. Data are requantized and Huffman encoded (compressed). The data processing on the ground will remove cosmic-ray spikes, bias and the smear produced during readout of the CCD, since there is no shutter. Differential ensemble renormalization will be performed to remove common-mode signal variations due to sky background effects such as zodiacal light and gain variations in the electronics. The flux time series will be analyzed for threshold-crossing events. These events will then be further scrutinized to determine which are consistent with transits and those that are simply false positives, such as grazing eclipsing binaries. Follow-up observations will be performed to further eliminate false positives, such as background eclipsing binaries.

Other Results from the Data

Follow-up radial-velocity observations with a precision of about 300m/s will be used to differentiate between planetary transits and grazing eclipsing binaries. High-precision radial velocity observations will provide masses for giant planets and even for short period terrestrial mass planets (Rivera et al, 2005, Mayor, 2005). For binary cases, the high precision photometry will be capable of detecting extreme mass ratios, e.g., an A-dwarf orbited by a late M-dwarf with M_2/M_1~0.02. We expect to detect 1000 to 1500 eclipsing binaries and produce high precision light curves for them.

Other astrophysical results we expect from the data include: Measurement of p-mode oscillations, which provides a window to the stellar interior, namely, the stellar mass and age (Brown and Gilliland, 1994); Measurement of stellar activity yielding star spot cycles, white light flaring data and in particular the frequency of Maunder minimums of solar analogs, which has implications for terrestrial climatic changes and paleoclimatology; Measurement of stellar rotation rates providing an extensive data set for correlation with other measured characteristics especially those already provided from the *Kepler* stellar classification program; Measurement of cataclysmic variables providing data on pre-outburst activity, which is typically too low to have been previously seen; and Measurements of active galactic nuclei variability at a much lower level, which has implications on "engine" size in BL Lac, quasars, blazers. Thus, *Kepler* will provide a wealth of photometric results that can be used to address a broad range of astrophysical questions.

Community Access and Participation

The community can participate in the mission in two ways, either through accessing the data archive or by proposing additional objects to observe.

All mission data will become available to the community through a data analysis program. Data will be accessible through the Multi-mission Archive at Space Telescope (MAST) for at least ten years after the end of the mission. The primary content of this archive will be the calibrated light curves for all objects observed during the mission life time, approximately 170,000 for at least the first year and 100,000 for the remainder of the mission. Data will be in the form of flux time series (light curves) for each object. Original pixel data will also be available to permit investigations such as astrometry or for those who prefer to conduct there own photometric processing. A data release policy has been developed to release mission data at the earliest time that allows for data calibration and validation and ensures against false-positive planetary detections. The first three-month data set will be released approximately one year after commissioning and then supplements will be released annually. Publicly released *Kepler* observations will be freely available to all interested parties for data mining from the MAST.

There will also be a guest observer (GO) program, whereby scientists can propose to observe objects that are not already being observed as part of the *Kepler* planet search. Particular objects of interest to the community need to be specified, since only the data for the pixels of interest for the selected objects will be transmitted, processed and archived. One can assume that *Kepler* will already be observing most late-type-dwarf stars down to about R=15 and for M-dwarfs down to perhaps R=16. All proposed objects must be in the *Kepler* FOV. The FOV will not be moved. A tool for finding whether an object is on or off of a CCD can be found on the *Kepler* web site at http://Kepler.NASA.gov/sci/GODAP.html. Objects can be brighter or fainter than the nominal dynamic range, which was chosen strictly for terrestrial planet detection reasons. The duration of the observation can be from three months to the length of mission based on the scientific justification. Up to 3,000 objects are set aside for the GO program at fifteen-minute cadence and an additional 25 can be assigned at one-minute cadence. All GO objects will be processed with the standard pipeline and then placed in the archive.

Summary

The *Kepler Mission* will observe more than 100,000 dwarf stars continuously for four or more years with a precision of 17 ppm (20 ppm when including 10 ppm for stellar variability) in 6.5 hours for an R=12 G2V star. The mission design is based on reliably detecting one-Earth radius planets in the habitable zone of solar-like stars. The mission will identify all eclipsing binaries in the FOV, with the expectation of detecting extreme mass ratio cases. The scientific community will have access to the entire mission data set with full photometric precision. The community can propose to observe additional objects within the field of view that are not part of the planetary detection program. Launch is planned for 2008.

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